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Initial measurements are reported for the Mercury laser system, a scalable driver for rep-rated inertial fusion energy. The performance goals include 10% electrical efficiency at 10 Hz and 100 J with a 2-10 ns pulse length. We report on the first Yb:S-FAP crystals grown to sufficient size for fabricating full size (4 x 6 cm) amplifier slabs. The first of four 160 kW (peak power) diode arrays and pump delivery systems were completed and tested with the following results: 5.5% power droop over a 0.75 ms pulse, 3.95 nm spectral linewidth, far field divergence of 14.0 mrad and 149.5 mrad in the microlensed and unmicrolensed directions respectively, and 83% optical-to-optical transfer efficiency through the pump delivery system.

I. Introduction

The Mercury laser design is based on creating a scalable architecture for inertial fusion energy applications (Orth and Payne[1]). This architecture builds on our knowledge of flashlamp-pumped glass laser systems such as Nova, Omega, and the National Ignition Facility, namely multi-pass amplification, energy storage and extraction, pumping, linear and nonlinear wavefront distortions, frequency-conversion, and beam smoothing. This diode-pumped solid state laser approach adds several imposing challenges including: repetition rate, efficiency, reliability, and cost. It is noteworthy that Matsui et al. [2] are developing a Nd:glass diode-pumped zigzag driver (10 J at 10 Hz) for IFE, and have recently demonstrated 2.7 J at 2.5 Hz. To achieve the Mercury goals of 10 Hz operation at 10 % electrical efficiency, three major technologies were developed: reliable high-peak-power diode arrays, high optical quality Yb^{3+}:$Sr_5(PO_4)_3F$ (Yb:S-FAP) crystalline slabs, and efficient helium gas cooling of the gain media. Integration of these technologies into a modular, scalable architecture will add reliability to the operation of Mercury system, and great impact to the modest output energies at this scale. These technologies will allow us to step beyond the single shot devices of the past three decades to yield efficient inertial fusion drivers for the power plants of the future.

II. Architecture

The optical layout of the amplifiers, pump delivery, optics, and relay telescopes was arranged to reduce the probability of damage, and yet create a compact laser system. Since the packaging of the diode bars causes the diode light to exit at an angle of 55º, the diode arrays were tilted to accommodate for this angle and split into two elements to allow for the passage of the 1047 nm extraction beam through the center as shown in Fig. 1. A unique challenge to the gas-cooled design of Mercury was in the coupling of the diode pump light to the amplifier medium. We chose a pumping scheme in which the diode pump and extraction light are collinear. This design minimizes the number of optics in the beam line relative to earlier designs thereby lowering the overall B-integral of the laser extraction, while maximizing the pump transport efficiency. The diode array light is guided to the amplifier through multiple reflections within a hollow lens duct and homogenizer. In designing these optics, the diode tiles are first arranged to produce a uniform angular distribution at the input of the lens duct. Next, the duct length is optimized for maximum transfer efficiency and the output aperture size is nearly matched to the beam size. A slightly larger aperture (3.2 x 5.2 cm) is needed to allow for the passage of the angularly multiplexed extraction beams. Finally, the homogenizer length is optimized to create a homogeneous near field profile at the exit. A ray tracing code was used to find the optimal configuration of the tiles with the result being an arrangement of six tiles wide by six tiles high in each backplane. Measurements of this system resulted in a transport efficiency of 77% in a 3x5 cm area at the first amplifier slab. Using a 4-pass double amplifier system, a 40 mJ narrowband input pulse will be amplified to 100 J with an extraction efficiency of 63%, and a pump optical to optical efficiency of 22%. This is possible because of the low saturation fluence of Yb:S-FAP (3.2 J/cm^2), which allows efficient extraction at approximately 7 J/cm^2, a fluence level that is well below the damage threshold.

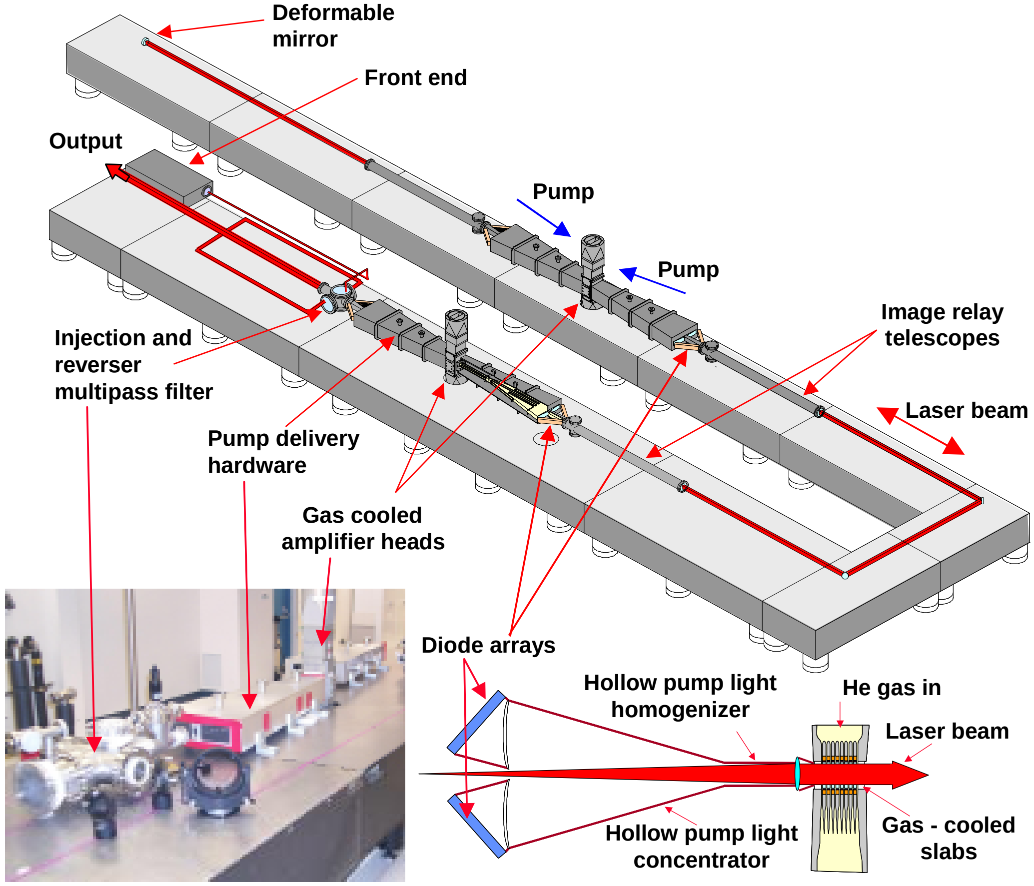


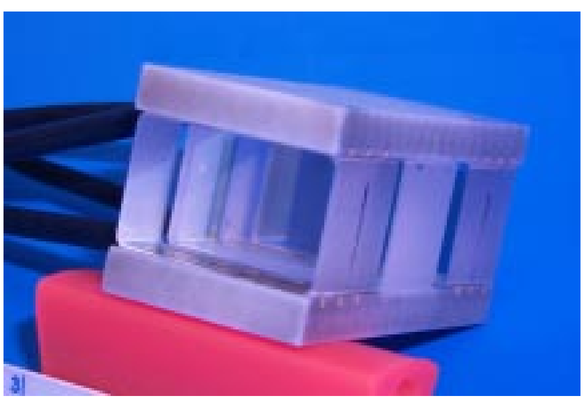
Fig. 1. The architecture design for the Mercury laser employs eight 80 kW diode arrays arranged in a backplane design. In addition, one-to-one telescopes are used to relay image the extraction beam from one amplifier to another. One lens in each telescope is located near the amplifier to reduce modulation, thereby helping to avoid optical damage.

In order to extract all the stored energy, a four-pass configuration is employed by angularly multiplexing the beams, which eliminates the need for a large-aperture high average power

Pockels cell at the output where energies are high. An image relayed system is used since optics which are located out of the image plane encounter greater intensity modulation on the beam and are thus at higher risk for optical damage. One lens of each one-to-one telescope is located very close to the amplifier to help reduce modulation and thus prevent optical damage. After the final pass, where the average fluence exceeds 7 J/cm^2, the out of relay output lens provides a 2X magnification to reduce the peak fluence to acceptable levels.

Extensive ghost and amplified spontaneous emission analysis was performed, validating the current architecture and setting constraints on optical quality, surface reflectivity, wedges, and the extinction required of a Pockels cell in the reverser (an image relay beam path which turns the beam and re-injects it for the 3 and 4th pass through the system). Though the Pockels cell sees relatively low energy pulses (< 0.5 J/cm2), the average power loading (100W) requires an advanced design since thermal birefringence compromises the extinction ratio of the cell. A design was explored in which two nearly identical KD*P crystals are oriented with a 90º rotator between them such that the thermally induced birefringence is nearly cancelled. The average power Pockels cell shown in Fig. 2 has an aperture of 1.5 x 2.5 cm, is capable of extinction of 200:1 at an incident power of 100 W, and will be used to prevent ghost beams from reaching high levels of amplification.

The ytterbium doped S-FAP slabs have a 1º wedge between faces, and have 5º canted edges to suppress: parasitics, etalon effects, stimulated Brillouin, and stimulated Raman scattering. Preliminary laser propagation modeling of the full system, using the MIRO code developed by scientists at CEA in France (adapted from Prop 92 at LLNL), indicates that greater than 90% of the beam is contained in a 5x diffraction limited spot with a B-integral of 1.7 for a 2 ns pulse. We are currently updating our thermal model to include the pump deposition profiles for the new wedged slab design and will incorporate these dynamic distortions in our MIRO propagation model (earlier models gave 3.6 waves total thermal distortion for the 4 pass system). A deformable mirror will be used in the final system to help correct for low order distortions.

a) 

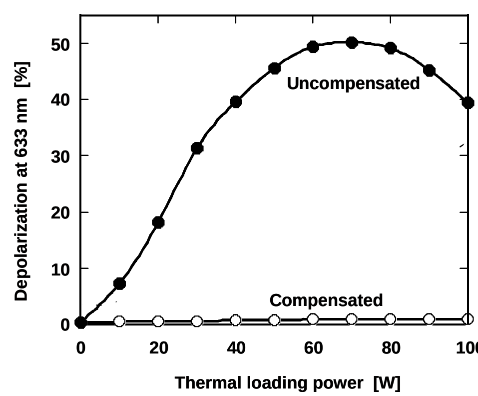
b) 

Fig. 2 a) Picture of the thermal birefringence compensated average power Pockels cell, b) A plot showing the advantage of birefringence compensation by demonstrating extremely low depolarization loss up to 100 W average power.

III. Crystal Growth

Recent breakthroughs have been made in the growth of the ytterbium doped strontium fluorapatite (S-FAP) crystals. Current growths have produced four 3.4 cm diameter boules free of major defects. These boules have been fabricated into ½ size amplifier slabs (Fig. 3a and 3b), which will then be diffusion bonded together by Onyx Optics to achieve full-scale 4 x 6 cm amplifier slabs[3]. These Czochralski grown crystals were initially plagued by a number of defects including: cracking, cloudiness, bubble core defects, grain boundaries or slip dislocations, anomalous absorption, and crystal inclusions. The remaining defects include a small annulus of inclusions on the outer perimeter of the boule, and a small number of bubble core defects concentrated to the center of the boule. Our current method of fabricating ½ slabs allows us to work around the defects while continuing to explore ways to eliminate them. The first full completed amplifier slab of Yb:S-FAP is anticipated by October, 2001.

a) 

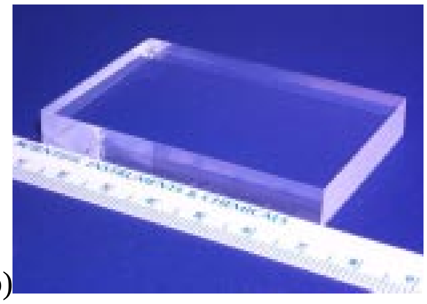
b) 

Fig. 3 a) Sub-slab components from a Livermore boule to be fabricated into full size amplifier slabs, b) A bonded full size slab from a Litton-Airtron boule currently being finished.

IV. Diode Lasers

A 23-bar monolithic diode laser package was developed for the Mercury Laser, referred to as Bars And Springs In Slots (V-BASIS)[4]. In this scheme, diodes are soldered to a V-groove etched silicon wafer, which is then bonded to a Molybdenum block for structural support and heat sinking. Next microlens arrays are precision mounted onto the assembly to increase brightness. The final unit or “tile” is then mounted to a water-cooled copper backplane. Electrical feed-throughs and coolant channels are located inside the backplane to increase the diode tile packing density and the overall brightness of the array. High peak irradiance is desirable which leads to compact diode spacing. However, the diode spacing must be kept to some minimum spacing to accommodate the 1 mm cavity length of the bars. The package is consistent with our low duty factor (1%) and the need for low cost packaging (6624 diode bars in the system). The V-BASIS design, which balances both of these requirements and allows for compact mounting onto the copper backplane cooler. Each backplane delivers up to 80 kW of peak power in a 750 μs pulse with a divergence of 1° in the microlensed axis, 9° in the unmicrolensed axis, and a 4 nm bandwidth. Recent experiments based on Coherent bars demonstrate that these diodes can operate with an electrical efficiency of at least 45% per bar. Experimental life tests of a 23 bar V-BASIS tiles at 10 Hz and 115 W yield a lifetime of greater than 10^8 shots.

V. Activation

Initial activation included investigation of several key components in the system. Amplifier slabs are mounted into aerodynamic vanes[5] that accelerate the gas to produce turbulent flow across the amplifier slabs for maximum cooling, and then decelerate the gas with minimum vibration. The pressure balance across the eight gas channels in an amplifier head was found to be an average of 0.775 psi pressure drop with maximum variations of +0.056 and –0.052 psi, which is adequate to preclude the formation of wake disturbances as the flows merge at the trailing edge of the vane. These results were confirmed experimentally by measuring the differential wavefront distortion of a gas-cooled amplifier head loaded with surrogate Nd:glass slabs and found to be less than λ/16, which for a two amplifier system corresponds to half wave distortion due to effects of gas flow.

Currently two backplanes have been activated (160 kW total) and we hope to complete fabrication of two more backplanes by mid-October. Results for the initial backplane characterization are shown in Figs. 4. The measured droop (6 %) in the temporal pulse, the linewidth (4.2 nm) of the output spectrum, and far field divergence (13 x 146 mrad) of the full backplane are well within the design point requirements. Measurements of the transfer efficiency and pump homogeneity after the pump delivery system (diode lenses, lens duct, homogenizer, and laser transport lens) at the input to the first slab are depicted in Fig. 5. The transfer efficiency was experimentally measured to be 83%, which is similar to the ray-trace prediction of 86%. The pump uniformity at the amplifier locations matches well with ray trace predictions as can be seen in the overlay of the lineouts in Fig. 5b.

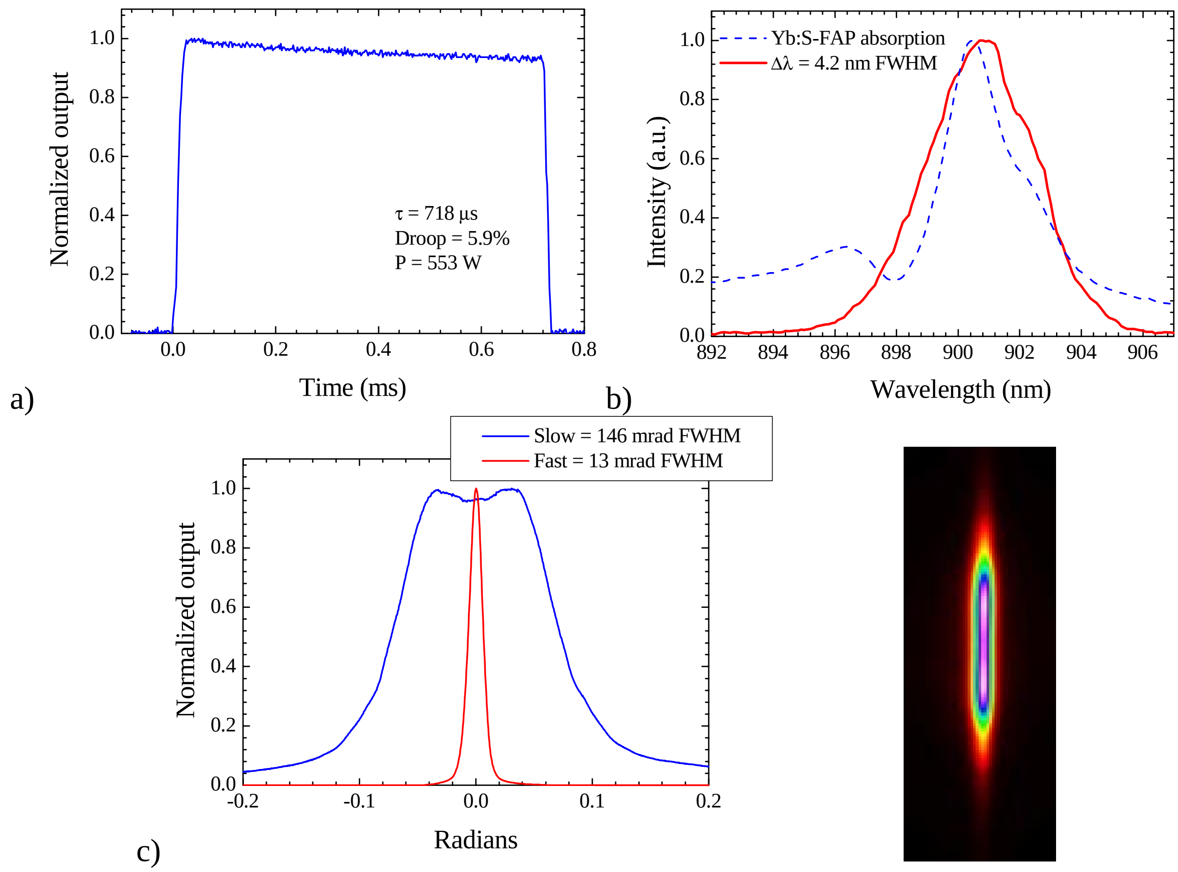


Fig. 4 a) The power droop of temporal pulsewidth for each backplane is within specifications (< 10%) for the current backplane cooling design. b) The linewidth of the diode backplanes overlaps well with Yb:S-FAP pump linewidth of 4.6 nm. c) The divergence matches predictions and ensures a longer Rayleigh range after the homogenizer.

Our front end laser, based on a Continuum master oscillator power amplifier system, produces over 500 mJ in a 20 ns FWHM pulsewidth. The spatially gaussian profile will be apodized to produce a spatially flat-topped supergaussian profile. This front end laser will be used in preliminary gain experiments employing surrogate Nd:glass slabs to measure gain uniformity and wavefront distortion. These experiments will be used to validate beam propagation codes as well as the optical layout of the architecture and allow for fine-tuning the system before the amplifiers are assembled with Yb:S-FAP.

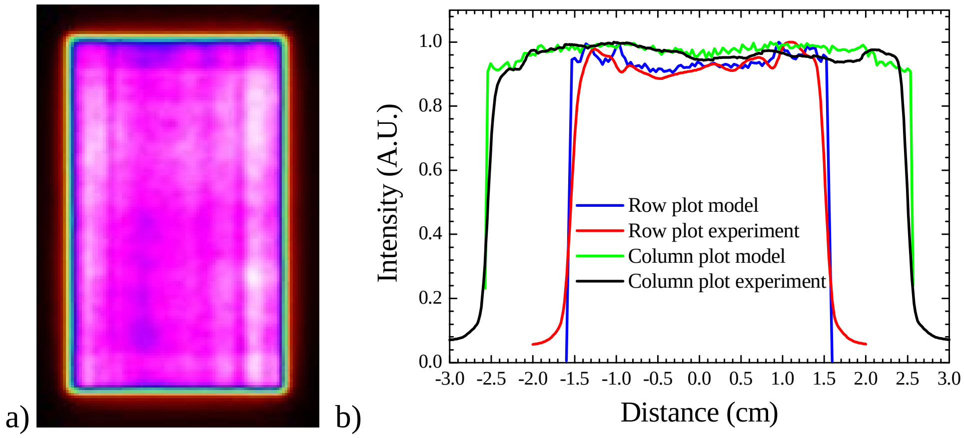


Fig. 5 a) A 4 x 6 cm intensity plot of the output of the pump delivery system shows a nearly homogeneous output. b) Lineouts of the plot show the intensity variation is less than ±3% in the vertical direction and approximately ±8% in the horizontal direction.

VI. Summary

Initial measurements were reported for the Mercury laser system, a scalable driver for inertial fusion energy. The first Yb:S-FAP crystals of sufficient size to fabricate full aperture amplifiers have been grown with four crystals in various stages of fabrication. The first full diode backplane and pump delivery system was completed and tested with the following average results: 6% power droop, 4.2 nm spectral linewidth, far field divergence of 13 mrad and 146 mrad microlensed and unmicrolensed axis respectively, and 83% transfer efficiency through the pump delivery system.

We would like to thank Mark Emanuel and Jay Skidmore for their prior work developing the laser diodes. This article is dedicated to the memory of Howard Powell for his unwavering support of the Mercury Laser and his personal commitment to inertial fusion energy. This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

VII. References

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